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Delineation of Fractures in Igneous Rock Masses Using Common Offset Radar Reflection

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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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CONTENTS

ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	min	minute
dB	decibel	m/ns	meter per nanosecond
GHz	gigahertz	ns	nanosecond
m	meter	pct	percent
MHz	megahertz	V	volt

DELINEATION OF FRACTURES IN IGNEOUS ROCK MASSES USING COMMON OFFSET RADAR REFLECTION

By Michael J. Friedel,[1] James J. Jessop,[1] and Richard E. Thill[2]

ABSTRACT

As part of an investigation aimed at improving the health and safety and competitiveness of the mining industry, the U.S. Bureau of Mines evaluated the application of common offset radar profiling, using a 250-MHz ground-penetrating radar (GPR) system, for the detection of fractures in igneous rock. A series of radar reflection surveys were conducted to detect and delineate the extent of fracturing at various granodiorite and gabbro quarries and outcrops located in Minnesota. The application of radar profiling for detecting joints, sheeting fractures, shear zones, and depth to water table was demonstrated to be feasible with minimal processing. Radar reflection interpretations were verified by visual inspection of the rock mass and field mapping of local structure. The radar reflection section provides a simple, rapid, and cost-effective means for mapping of shallow (less than 10 m) small-scale fractures (greater than 0.25 cm) in igneous rock masses (characteristic of velocities between 0.061 m/ns for gabbro and 0.125 m/ns for granodiorite). Depth or distance estimates to fractures are within 10 pct of the actual, and time-shift compensation is necessary only when topographic irregularities exceed 30 cm.

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INTRODUCTION

Geosensing is an area of considerable interest in the U.S. Bureau of Mines' research program. One of the objectives in ground control research is to detect and delineate anomalous strata and ground conditions and to use geosensing for the characterization and classification of rock masses. In accord with its mission to help resolve health and safety and productivity problems facing the mining industry, the Bureau evaluated the applicability of ground-penetrating radar (GPR) for detecting fractures and other subsurface geologic structures in igneous rock masses. The investigations, conducted in cooperation with the Minnesota Department of Natural Resources and the Cold Spring Granite Co. as co-interested parties, evaluated the use of GPR for site characterization and flaw detection at potential quarry sites.

In the past, GPR has been successfully employed to resolve structural features in both soil and bedrock (*1-3*)[3] and to located buried pipes and cables (*4*). Related investigations have concentrated on assessing the feasibility of GPR for detecting coal (*5*), granular deposits, and sea ice thickness in permafrost regions (*6*). Recent studies have also confirmed the usefulness of GPR for delineating tunnels (*7-8*) and abandoned mines in granitic and limestone rock masses (*9-10*). This report discusses results from GPR field investigations involving the detection of fractures, joints, and the water table in active and potential granitic quarry sites in central and northeastern Minnesota (fig. 1).

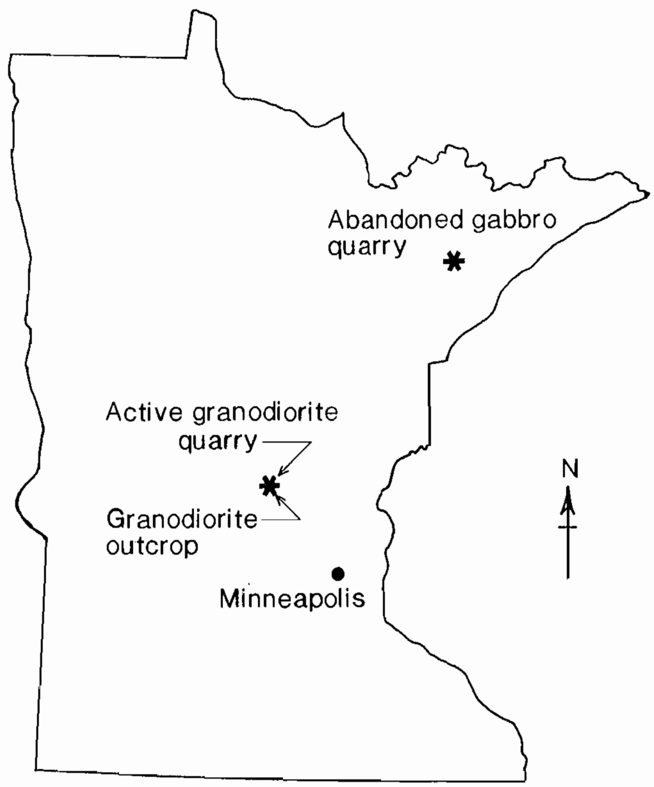

Figure 1.—Common offset radar reflection sites in central and northeastern Minnesota.

RADAR PRINCIPLES

GPR is an electromagnetic technique that responds to changes in electrical properties in the earth. The transmission, reflection, refraction, and diffraction of an electromagnetic wave is defined by the Maxwell equations. These equations describe the electric and magnetic fields of an electromagnetic wave over a broad range of frequencies in terms of the electrical and magnetic properties of the material that the wave travels through. In the electromagnetic spectrum, the frequency range of radar energy lies between 1 MHz and 1 GHz. A comprehensive discussion of the principles affecting radar propagation is given by Bochicchio (*11*).

A GPR system can operate in either a monostatic or bistatic mode. In the former made a single antenna operates as both the transmitter and receiver of radar energy. The latter mode requires use of two antennas; one transmitting a radar source signal and one receiving radar energy. The transmitted radar pulse travels away from the transmitter until it counters a change in electrical properties, or electrical impedance. At this point, the energy is partitioned in one or more of the following modes: transmitted, reflected, refracted, and diffracted components. The time delay of these various waveforms sensed by the receiving antenna is a function of the (1) propagation velocity of the impinging wavelet through the rock mass, (2) depth to the impedance contrast, and (3) distance between antennas. Since the received radar pulse is a convoluted representation of one or more of these radar wave types, the ability to record useful information hinges upon the detection, resolution, and interpretive capabilities of the radar system.

The range and detection capabilities of a GPR system depend on the electrical properties and propagation characteristics of the materials, geologic noise, system characteristics, and enhancement of the data. Since the electrical properties of the rock mass are intrinsic, the operator must control characteristics of the source and/or receiver, or of the data display.

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

RANGE

The theoretical performance range for a radar wavelet propagating in granite was established using an electromagnetic forward model. Based on the modeled information, and using a dielectric constant of 10, an instrument dynamic range of 70 dB, and a center frequency of 250 MHz, results indicated a reflected radar pulse could be expected to travel a distance of about 45 m. These depths of penetration appear adequate for assessing stress-relief fracturing and blast-induced damage caused by the mining process. However, it should be noted that highly conductive media within the propagation path, such as water or clay, tend to absorb electromagnetic energy and drastically alter the radar range in rock.

RESOLUTION

Resolution (the ability to detect and define a target) depends on the transmitted signal character, i.e., amplitude and wavelength; the dielectric properties of the rock mass and contrast with the target; and the shape and character of the target, e.g., depth, shape, and size. Often resolution is expressed as a ratio of the minimum target dimension to wavelength. Since the primary targets of the investigation are fractures, of small aperture in igneous rock, it is important to maintain a radar wavelet of relatively high-frequency content. The important question then arises, What fraction of a wavelength, relative to the frequency content of the propagating radar wavelet, is sufficient to detect a fracture? The following relationships assist in the determination of the appropriate radar frequency band when the electrical properties of the rock mass are known:

$$\lambda = \frac{V_o}{f}, \quad (1)$$

and

$$V_o = \frac{C}{\sqrt{\epsilon_m}}, \quad (2)$$

where λ = wavelength, m,

V_o = velocity of a radar pulse propagating through the rock mass, m/ns,

f = frequency, MHz,

C = velocity of a radar pulse propagating through air (0.3 m/ns),

and $\sqrt{\epsilon_m}$ = dielectric constant of media.

Assuming a dielectric constant of 10 for granite (*10*), the wavelength would be on the order of 3.5 cm. Using the seismic analogy, where minimum resolution is about 1/32 of a wavelength, individual granite fractures (or zones of fractures) greater than 0.1 cm could be identified based on an impinging radar 250-MHz wavelet. The overall performance could be improved by (1) increased frequency content (the antenna used in this study has an output pulse that contains energy to roughly 500 MHz), (2) a strong rock mass-to-target dielectric contrast, e.g., if fractures were wet as opposed to air filled, and (3) the use of digital enhancement during data acquisition, e.g., signal stacking, analog filters, and an automatic gain control (AGC).

EQUIPMENT

The commercially available OYO model 2441, GEORADAR-1[4] radar system was used for the field investigations of fractures in igneous rock. The radar system consisted of a profiling recorder, oscilloscope control unit, two antennas, and associated cables. The OYO control unit has a fixed time-domain asymmetric broadband pulse with a center frequency of 250 MHz. The radar system can be operated in either a continuous or individual shot mode. The recorder can be operated in either a scan or wiggle trace mode. A pair of system-compatible antennas are shielded to improve the transmitted signal directionally. This reduces noise in the form of back reflections from overhead power lines, trees, etc. The system provides for both direct and time varying gains, and AGC to amplify the later, weaker signals that achieve greater penetration into the rock.

FIELD PROCEDURE

WARR SOUNDING FOR SYSTEM CALIBRATION

A Wide Angle Refraction and Reflection (WARR) sounding, analogous to a seismic walk-away noise test, was conducted to establish an optimum (1) high- and low-pass filter setting, (2) number of signal stacks, and (3) transmitting-receiving antenna offset for profiling. The radar system permits front-end noise reduction and wavelet shaping through proper analog filter settings. The high-pass filter is used to compensate for the low-pass characteristics of the rock mass. The high-pass filter

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

setting can be used to improve the significance of high-frequency energy and, hence, the resolution of fractures. In the presence of random noise, the stacking capability greatly improves the signal-to-noise (S/N) ratio.

The WARR sounding establishes the characteristic partitioning of wave modes, e.g., refractions and reflections, occurring at the study site. In this procedure, the transmitting antenna is held stationary. The receiving antenna is then moved to a predetermined distance from the transmitter, the radar wavelet is transmitted, and the convoluted wavelet is recorded. Subsequent receiving antenna stations correspond to a multiple (1, 2, ...N) of the initial source-to-receiver distance. Ideally, the receiving station spacing and total number of traces recorded are adjusted to clearly identify target reflections(s) and refractions yet minimize the total number of traces recorded.

Refracted wave modes identified in the WARR sounding calibrations permitted an estimate of the depth-distance relationships from the time-distance profile. The first arrivals recorded on the test profile were produced by energy traveling through the air (air wave). Subsequent arrivals showing linear moveout (time change with distance) correspond to refracted energy traveling along the surface of the rock mass (direct wave). The velocity associated with this direct wave could be used to compute the depth to reflections associated with fractures. Later arriving reflections from horizontal fractures display a coherent hyperbolic moveout. The range of offsets that allows these target reflections to be observed with maximum coherency, i.e., with minimum interference from source-generated noise and maximum amplitude, is the "optimum window," as described previously for seismic applications by Hunter (*12*). Once the range of applicable source-to-receiver offsets is identified, the spacing between profile stations can be determined.

PROFILING TECHNIQUE

The GPR bistatic profiling mode requires moving a source-receiver antenna combination of fixed spacing at uniform-distance increments along the survey path. The distance between subsequent profile stations is a function of the detail in subsurface coverage required. For the present study, a spacing of about 15 cm was found to be adequate, but this spacing probably could have been increased to 30 cm and still have provided sufficient detail (without losing lateral resolution) to image the fractures.

Since coupling variations exist because of irregular surface conditions, the phase of the transmitted signal varies on a trace-by-trace basis, and higher order filtering operations, such as spiking deconvolution, are rendered ineffective. Hence, only analog, front-end filtering and signal stacking were used during the data acquisition phase. The radar display therefore appears analogous to a seismic signal display for a wiggle trace in the variable area mode.

DATA REDUCTION

The velocity, V_o, of a radar pulse propagating through the rock can be determined by

$$V_o = X/t, \tag{3}$$

where X = distance between stations, cm,

and t = travel time to refractor, ns.

This value can be combined with the propagation velocity in air, C, to determine the characteristic rock mass dielectric constant, ϵ_m, using equation 2. The characteristic velocity of radar waves in the rock mass can also be used to statically correct or time-shift a trace by an amount, t_c, to account for changes in elevation. Thus,

$$t_c = -2Z_c/V_o, \tag{4}$$

where Z_c = depth to datum.

To accurately assess damaged and intact volumes of rock, it is necessary to convert the time-distance radar section to a true depth-distance radar section. Here, it is important to recognize that the travel times to all reflectors have two-way (down-going and up-going component) times. Assuming homogeneous rock blocks, the corresponding depth to a horizontal reflector, z, can be calculated, based on the common depth point method (*13*) by

$$Z = \frac{\sqrt{t_2^2 x_1^2 - t_1^2 x_2^2}}{4\left(t_1^2 - t_2^2\right)}, \tag{5}$$

where t = time to a reflector,

x = distance between source and receiver,

and 1, 2 = indices referring to two different antenna separations.

When depth is determined, the average velocity in the rock mass can be calculated using a delay time for antenna separation at zero, i.e., zero offset given in a WARR sounding.

FIELD RESULTS AND DISCUSSION

FRACTURE DETECTION IN ST. CLOUD GRANODIORITE

The St. Cloud granodiorite tests were conducted at two properties owned by Cold Spring Granite Co., St. Cloud, MN. The first set of investigations occurred at an active quarry, where operations involve drilling and blasting of St. Cloud gray granodiorite (also called Charcoal granite) from the rock mass. The local geologic structure is characterized by faulting and fracturing attributed to tectonic forces, stress relief from blasting, and uplift. Local faults are continuous throughout the study area and include a zone of sheared rock. Fault surfaces are often chloritized and contain minor amounts of clay, whereas the stress-relieved fractures are clean, having apertures ranging from 0.25 cm to several centimeters (*14*).

The initial set of radar tests was conducted along the surface directly above the north face highwall at the Charcoal quarry No. 3 pit. Field investigations began with a WARR sounding conducted over a prominent horizontal fracture at a depth of roughly 2.4 m from the surface. The survey included 60 stations at 15-cm station intervals, with band-pass filtering between 160 MHz and 400 MHz, averaging of 16 stacks per trace, AGC, recording time window of 200 ns, and a 0.2-ns sample interval. The radar test results show several wave modes in figure 2; a weak

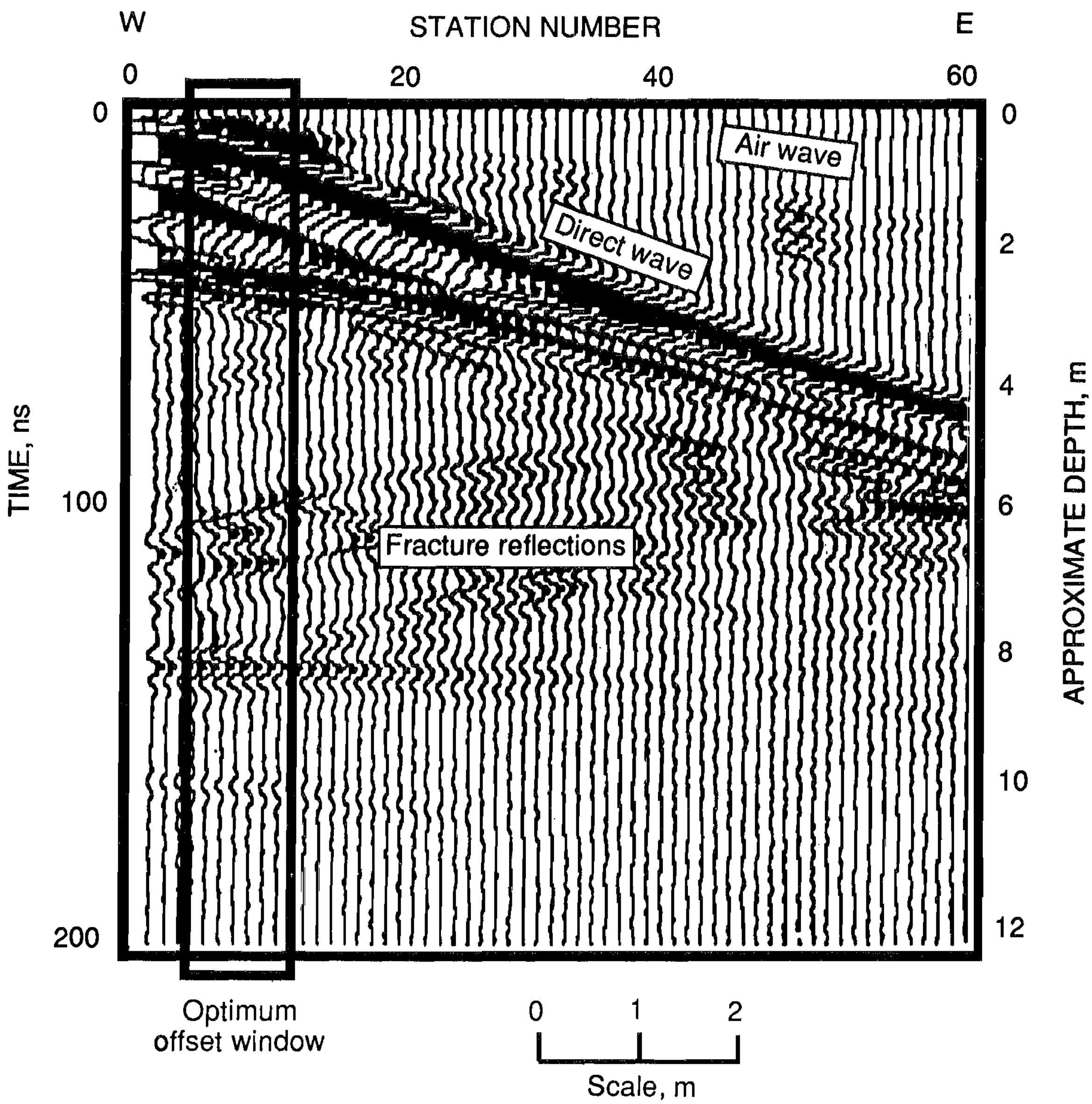

Figure 2.—WARR sounding conducted at north face of Charcoal granite quarry No. 3.

air wave, indicating the effectiveness of shielding, and a prominent, coherent direct wave. The refraction, showing linear moveout, is attributed to radar energy traveling along the surface of the rock mass. The computed velocity associated with radar energy propagating through the granodiorite was determined to be roughly 0.128 m/ns. Substituting this value into equation 2 gives a dielectric constant of 5.5. These values agree with those cited in the literature (*10*).

Apparent reflections from fractures occur at zero offset travel times greater than about 38 ns, corresponding to depths in excess of about 2.4 m. Any attempt to image fractures at lesser depths would be masked by the strong air- and ground-coupled radar energy. The most distant reflection, having very weak amplitude, occurs at a travel time of roughly 162 ns. This gives a depth of penetration of roughly 10 m. The optimum offset window was determined to exist between traces 4 and 10, where maximum coherency occurred for the majority of reflections arising from a horizontal and inclined set of fractures. Since the first trace is offset by 0.6 m, the closest distance to which the antennas could be placed, the source-to-receiver offset range is 1.2 to 2.1 m.

A spectral analysis of trace 15 from the north face WARR sounding indicates that broadband energy exists to 275 MHz with a primary frequency band between 50 and 200 MHz (fig. 3). Based on the spectral analysis of radar records, it is clear that sufficient radar energy can be propagated to depths on the order of 10 m, with sufficient resolving power to detect both horizontal and/or inclined fractures in granodiorite.

Figure 4*A* gives the approximate locations of fractures mapped at the radar study site, along the north face of the Charcoal granite quarry No. 3. The unprocessed (raw)

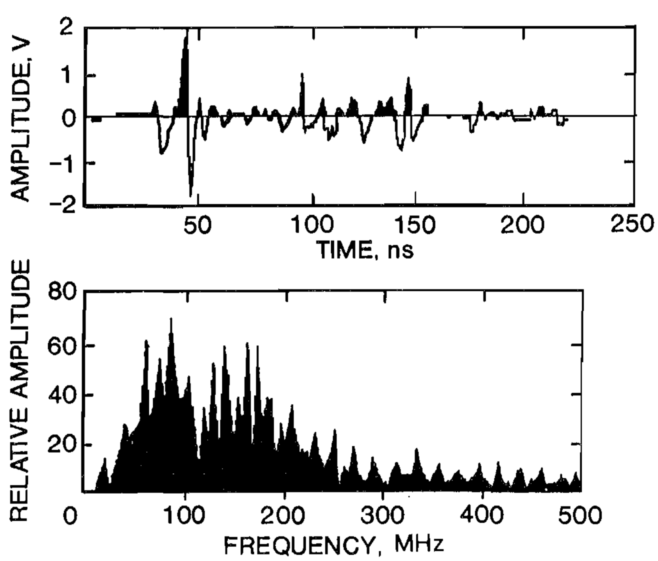

Figure 3.—Spectral analysis of WARR sounding conducted at north face of Charcoal granite quarry No. 3.

vertical common offset (CO) radar profile recorded at 120 stations along the north face is shown in figure 4*B*. The CO profile was conducted using the acquisition parameters suggested by the WARR survey with a source-to-receiver offset of 1.8 m. The uniformity in refracted energy occurring at a time between 0 and 38 ns, represented by the three dark continuous bands crossing the record, is typical of profiling along a flat-lying surface.

In general, when the ground surface is essentially flat and uniform, static corrections are not required for an accurate interpretation of the radar data. The slight change in elevation of roughly 15 cm occurring between stations 95 and 113, however, does affect the radar profile. Refracted energy is delayed in this zone, resulting in what appears to be a sag in the radar record. Clearly, topographic discrepancies in excess of 30 cm would require time-shift compensation to accurately portray subsurface features. Since most active quarrying operations work systematically with flat-lying benches, the potential for this sort of problem is reduced. When assessing prospective quarry outcrops over irregular topography, however, an elevation survey should be conducted to enable a time-shift correction to the radar data.

Several prominent reflections could be observed in the north face profile (fig. 4*B*). Between stations 0 and 45, a pair of inclined reflections occur; their travel times decrease eastward from roughly 60 ns. These reflections correlate with two shear fractures, dipping roughly 50° to the west, as observed from the quarry wall. Between stations 50 and 75, reflections at about 50 to 55 ns define a horizontal wedge-shaped block at depths of 3.2 and 3.5 m, respectively. The upper reflection coincides with a continuous fracture that dips slightly to the east and then flattens out near the end of the profile. The reflection amplitude associated with this fracture becomes strongest between stations 80 and 100 at a depth of about 3 m. As the fracture continues eastward it again has strong amplitudes between stations 115 and 120.

To enhance the interpretation of GPR record, the analog records were digitized and subsequently processed using BOMSPS (*15*). Figure 4*C* represents the CO radar section shown in figure 4*B*, following the implementation of refraction muting (0 to 42 ns), high-pass filter (150 MHz) with a cosine taper (24 dB per octave), and an AGC using a 25-ns window. Digital processing sharply defined reflection peaks and extended the coherency of reflectors over greater distances.

Figure 5*A* gives the approximate locations of vertical fractures occurring at various distances from the north face of the Charcoal granite quarry No. 3. the raw horizontal-slice CO radar profile, shown in figure 5*B*, was produced by traversing the front of the north face in Charcoal granite quarry No. 3, using the same acquisition parameters outlined above. This radar profile produced reflections sensitive to vertical joints and fractures, with the vertical face aligned at time zero. Refracted energy

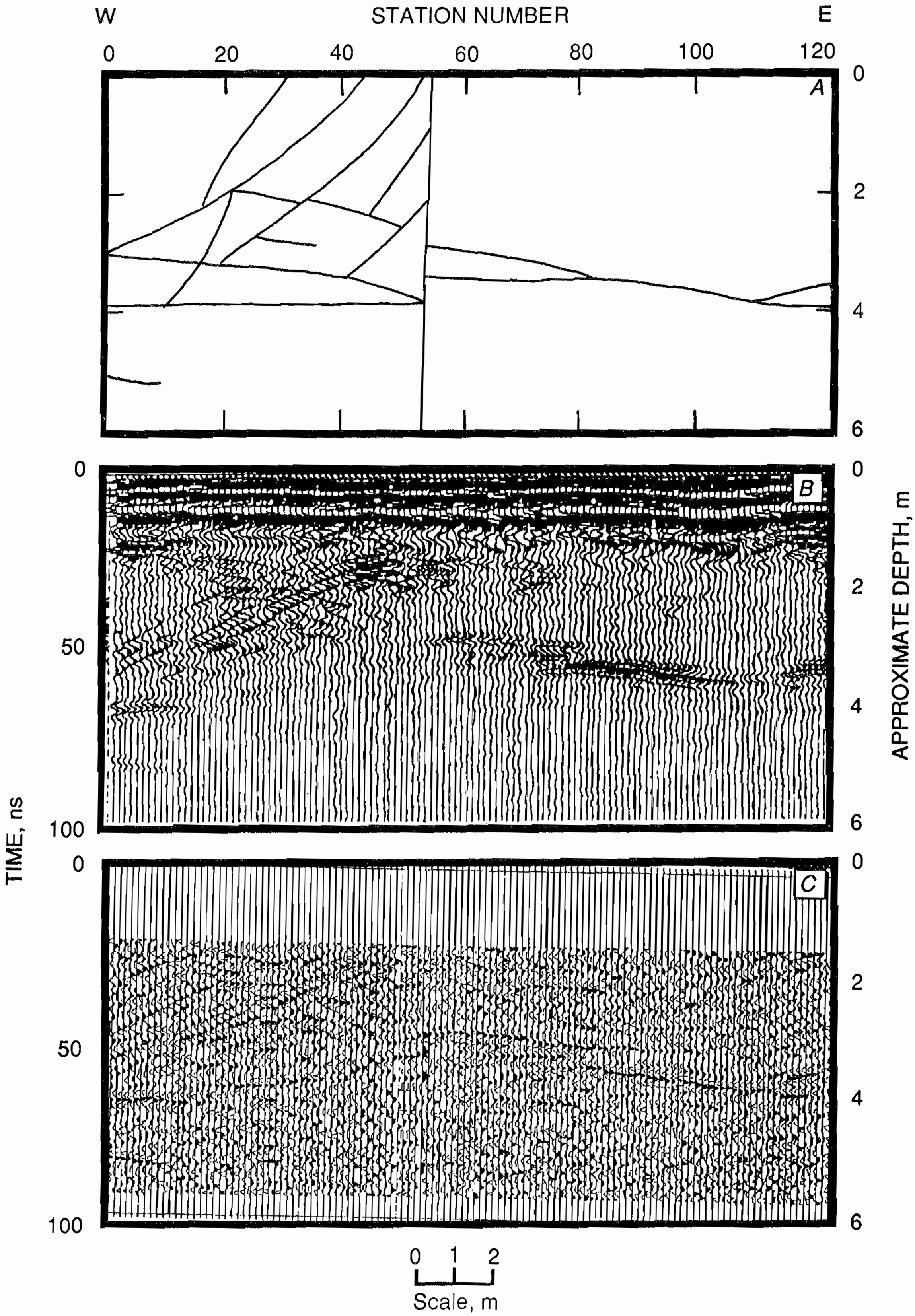

Figure 4.—Vertical analysis of fractures exposed along north face of Charcoal granite quarry No. 3. *A*, Mapped highwall fracture distribution; *B*, unprocessed vertical common offset radar profile; *C*, processed vertical common offset radar profile.

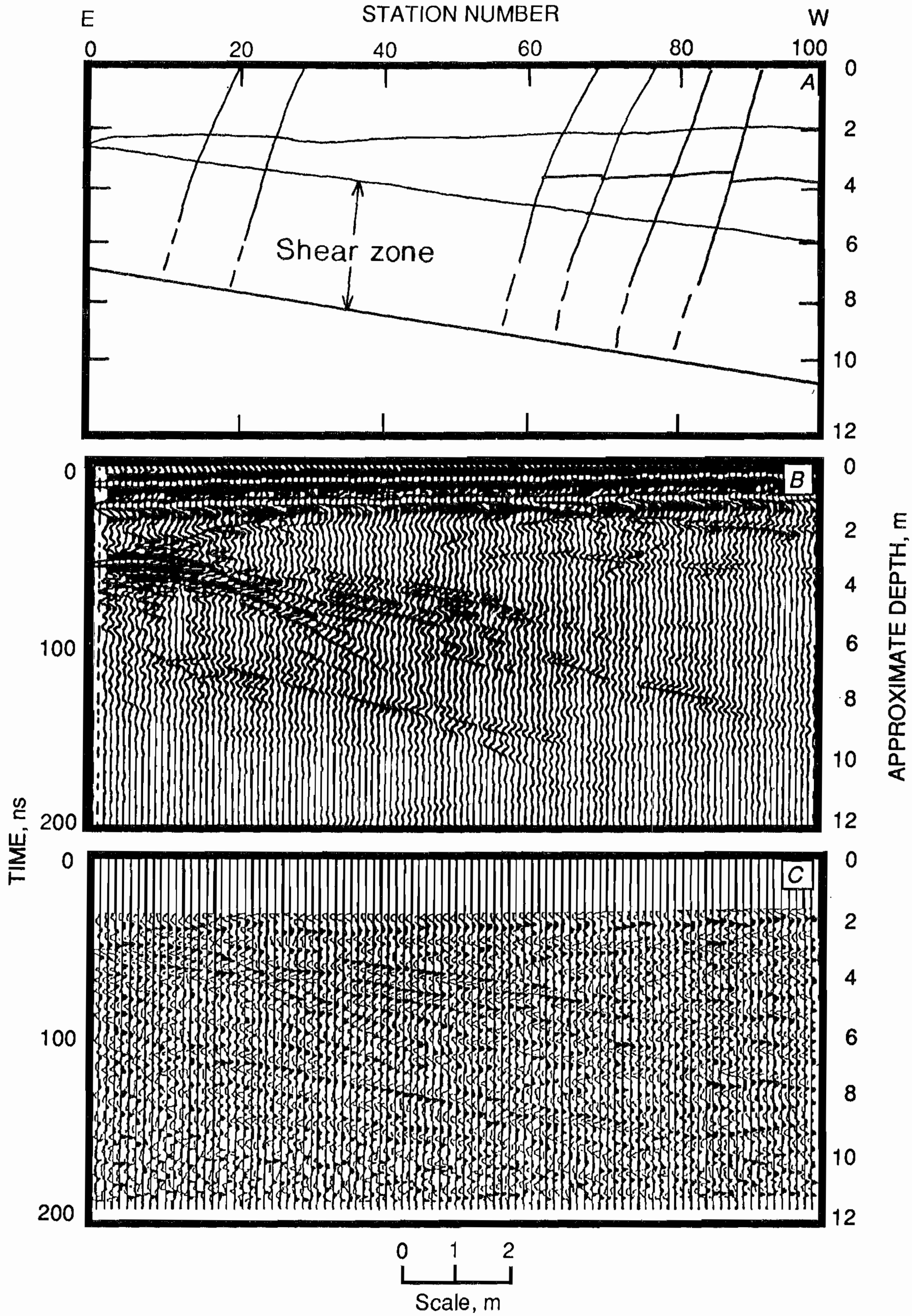

Figure 5.—Horizontal or plan view analysis of fractures from north face of Charcoal granite quarry No. 3 inward. *A*, Mapped and inferred vertical fractures; *B*, unprocessed horizontal common offset radar profile; *C*, processed horizontal common offset radar profile.

traveling along the surface of the rock mass appears as three coherent black lines crossing the radar section between 0 and 25 ns. Beyond about 25 ns, reflections occur, indicating the presence of vertical fractures detected inward from the quarry wall into the rock mass.

Strong reflections between stations 0 and 100 appear to define parallel sets of near-vertical joints or fractures that trend in a northwest direction from the quarry face (fig. 5B). These fractures could not be observed from the surface, i.e., top of the highwall, but agree with structural features previously mapped; the fractures are attributed to a local shear zone that trends N70W (*14*). The reflections with the greatest amplitude, between stations 0 and 10 at travel times between 50 and 75 ns, are interpreted as the back side of a block that terminated laterally at station 10. The lateral extent of this block is inferred from the diffractions that cross the parallel set of reflections. Two coherent shallow reflectors subparallel to the face exist along the western third of the record. The reflection occurring between stations 95 and 115 at a travel time of 43 ns corresponded to a visible fracture trace at a distance of about 1.5 m from the quarry face. The deeper reflection occurring between stations 65 and 115 at a travel time of 61 ns was also believed to be a near-vertical subparallel to the face at a distance of roughly 2 m from the face. The presence of this fracture could not be verified, however, because of the presence of a soil cover. The six vertical fractures begin at stations 20, 30, 70, 77, 85, and 92, and trend in a northeasterly direction inward from the face. Visual inspection of the highwall face revealed a fracture trace for each, confirming the radar interpretation.

Using the same parameters, the digitally processed radar record, shown in figure 5*C*, enhanced reflection peaks and extended the coherency of reflectors over distances throughout the profile (43 ns). It is interesting to note the continuity of a horizontal reflection extending from east to west. Only a portion of this reflection was present (between stations 100 and 110) in the previous unprocessed section. The presence of this vertical fracture was confirmed by trace observation at the horizontal surface of the highwall. The digital processing enhanced the radar data such that this vertical fracture, subparallel to the highwall face, could be traced along its extent. Additionally, the locations of fractures intercepting the vertical face (at stations 20, 30, 70, 77, 85, and 92) can be more easily located where the horizontal continuity is broken. Previously, the fracture occurring at station 20 was not apparent.

A second site investigation using radar was conducted at the Cold Spring Granite Co. Meridian property outcrop, near Cold Spring, MN. This test site was chosen to evaluate rock mass integrity for use as a potential dimension stone quarry site. A linear north-south traverse was conducted along the axis of the Charcoal granite outcrop. Measurement stations were at 15-cm intervals.

A WARR sounding was conducted that indicated the presence of several wave modes (fig. 6); a weak air wave at stations beyond 40 beginning at a time of roughly 75 ns, and coherent ground-coupled energy at all stations. Based on the slope of the air-rock refractor, the computed radar velocity for this site was determined to be roughly 0.125 m/ns. Substituting this value into equation 2 gives a dielectric constant of 5.8, which is consistent with the previous site. Also present in the WARR sounding are strong reflectors, between stations 1 and 35, occurring at a zero offset time between about 93 and 110 ns. This corresponded to a depth of roughly 5.8 to 6.9 m. Note that the moveout, i.e., change in travel time with distance, changes character; the moveout originally displays hyperbolic trajectory at near offsets and becomes linear at increasing distances. This behavior represents a change from reflected to refracted radar energy. Since high-amplitude and coherent reflections could be observed between all traces, any corresponding source-to-receiver offset could have been used. For this case, a source-to-receiver offset of 1.8 m was again chosen for profiling.

The CO radar profile resulting from the survey conducted at the Meridian outcrop is shown in figure 7*B*. The acquisition parameters are the same as those previously mentioned, except that the time window was extended to 300 ns. The primary event appears as a sequence of three reflection segments increasing in time from 53 ns at the east end to about 100 ns at the west end, corresponding to depths of roughly 3.3 and 6.3 m, respectively. This is believed to be sheeting—a stress relief fracture (fig. 7*A*) that developed as a result of glacial unloading. The numerous short-duration events extending away from the primary reflections along the lower side are interpreted to be diffractions. These diffractions occur in response to point sources, or in this case, discontinuous fractures occurring in this zone.

A second traverse, using the conventional scan mode, was conducted along the same survey line for comparison to the wiggle trace. The radar scan mode record obtained over the same profile segment is shown in figure 7*C*. While the fracture reflection and diffractions also appear in this record, they could easily have been overlooked without knowing their existence a priori. The additional primary features (greater than 150 ns) that appear as large, dark, continuous horizontal bands represent coherent noise. Although the scan mode can be done in about half the time it takes to do the wiggle trace CO mode, the noisy records hinder a rapid and meaningful interpretation. Hence, these results suggest that radar investigations in igneous rocks be conducted using the wiggle trace mode.

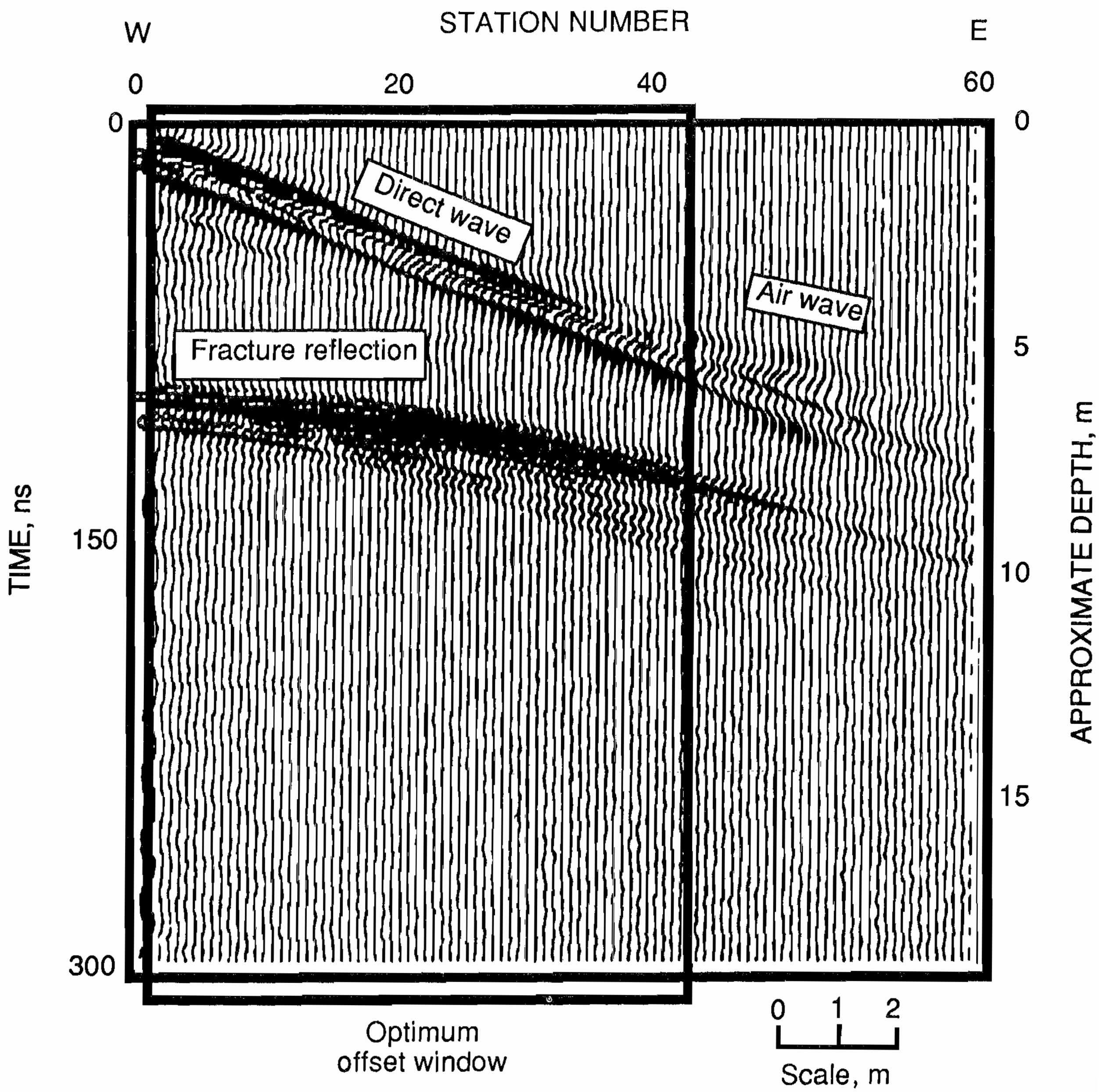

Figure 6.—WARR sounding conducted at outcrop near Cold Spring, MN.

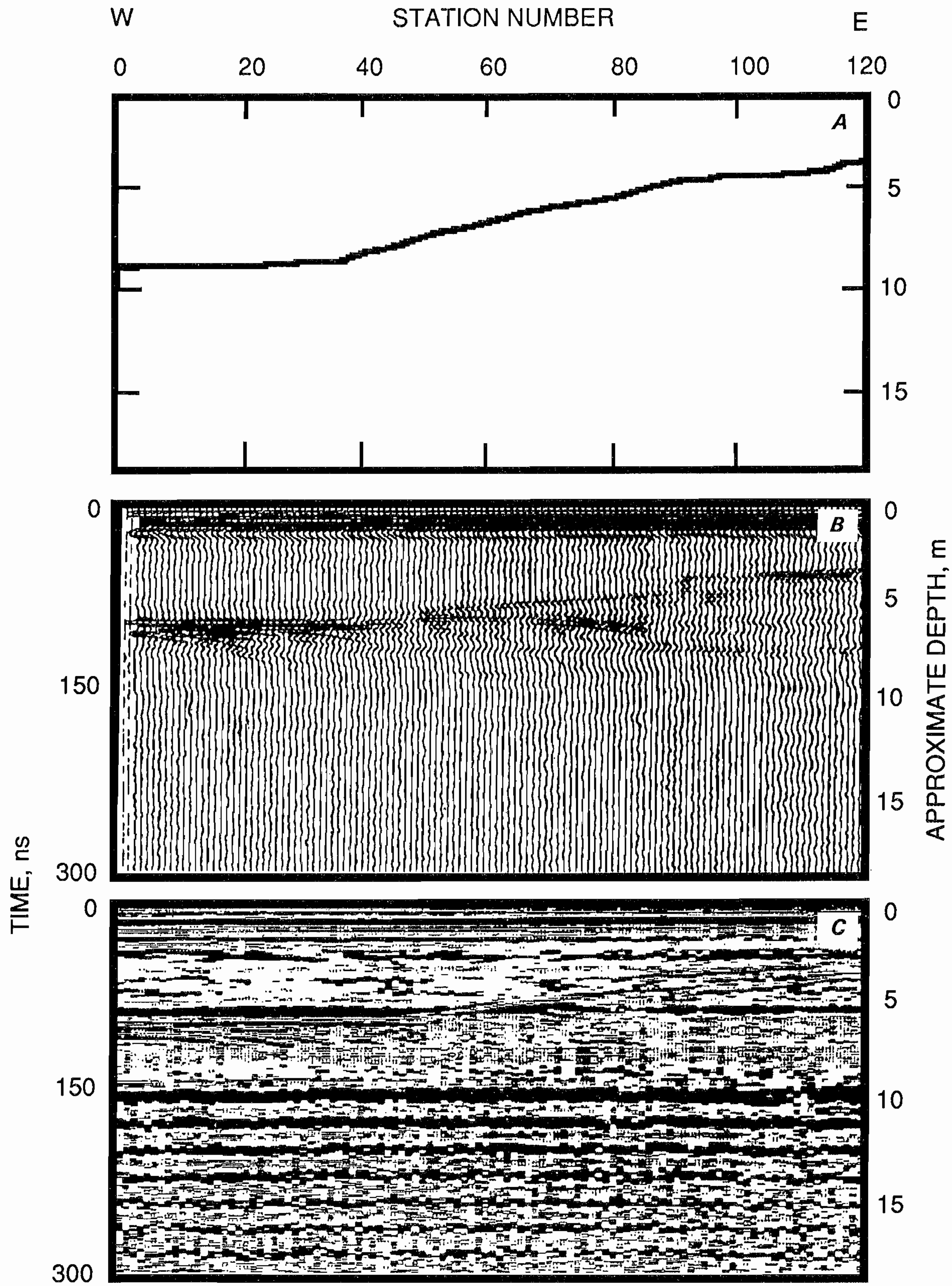

Figure 7.—Analysis of fractures in outcrop near Cold Spring, MN. ***A*, inferred fracturing; *B*, common offset radar wiggle trace profile; *C*, common offset radar scan mode profile.**

FRACTURE DETECTION IN DULUTH GABBRO

Another set of GPR radar investigations was conducted at an abandoned Duluth gabbro quarry site in northeastern Minnesota, in the SE1/4, NW1/4 of Section 13, T6N, R11W. The WARR sounding, conducted along a linear traverse at the top of a southeast face and 1.7 m above a prominent horizontal fracture, is shown in figure 8. Refracted air- and ground-coupled energy, a reflection arriving from a horizontal fracture at a zero offset time of about 56 ns, and a reflection arriving from the water table at a zero offset time of about 150 ns were apparent in the sounding. The optimum offset window exists between traces 7 and 12, giving source-to-receiver distances of 1.05 to 1.8 m. From this sounding, the velocity for radar propagation in the gabbro was determined to be roughly 0.061 m/ns, giving a dielectric constant of about 24. This value could not be substantiated, since there is no mention of any dielectric value for gabbro in the literature. The increase in dielectric property over that derived for granodiorite, however, can be attributed to the known existence of high amounts of disseminated copper and iron sulfides in gabbro.

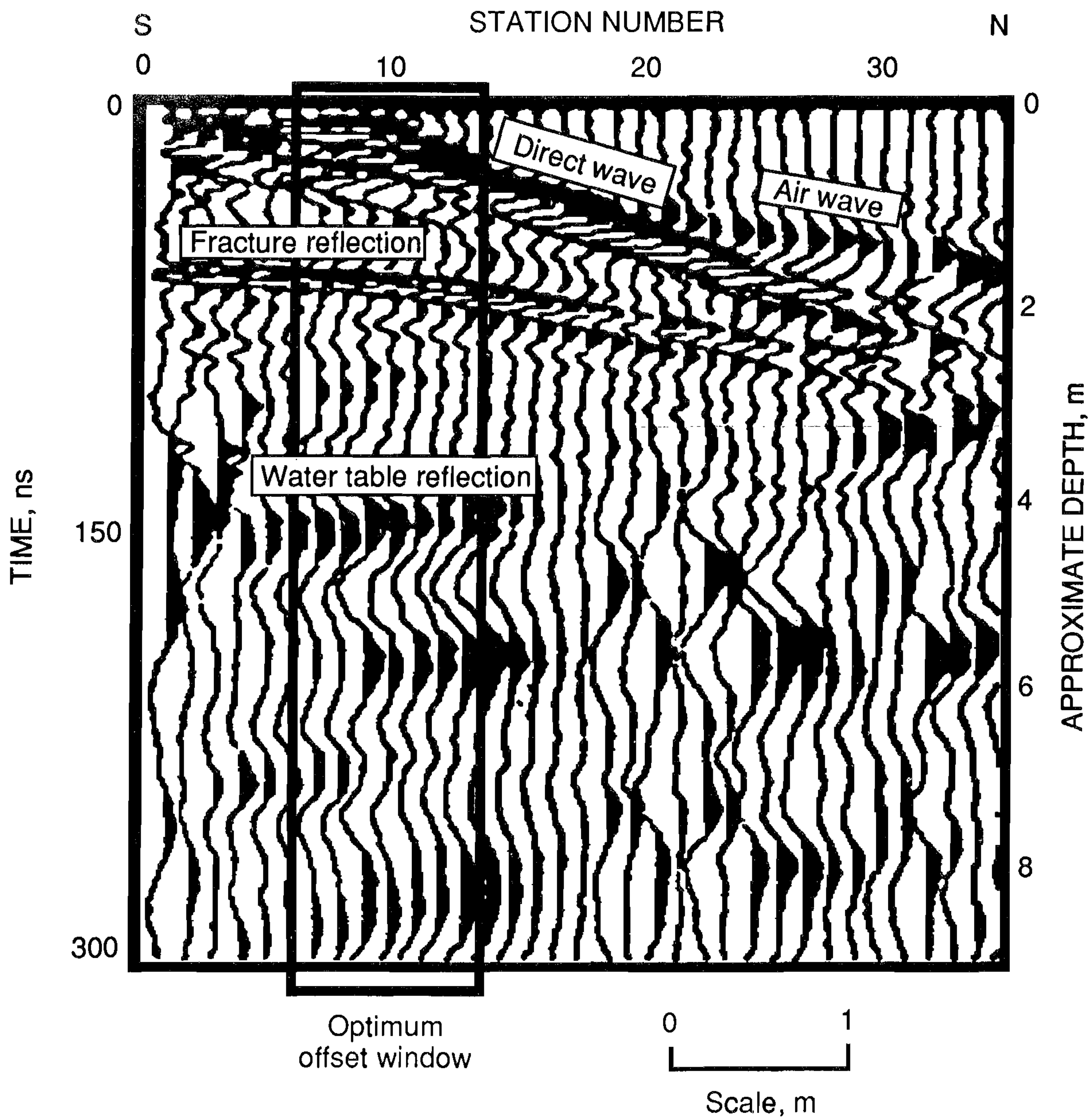

Figure 8.—WARR sounding conducted at abandoned Duluth gabbro quarry site in northeastern Minnesota.

Based on results from the WARR sounding, a CO radar survey was conducted at the top of the southeast face of the abandoned quarry. Figures 10*B* and *D* show the mapped fractures visible along the vertical face and the CO radar profile, respectively. The roughly 18-m linear traverse consisted of a source-to-receiver offset of 1.5 m, shot and group intervals of 15 cm, 120-MHz high-pass and 400-MHz low-pass filter settings, a 16-signal stack, and AGC.

Several horizontal and inclined reflection events are evident in this radar profile record. The inclined reflections dip inward from the north end, with several subparallel linear trends increasing in time to the south. These inclined reflections are interpreted as a plunging fracture. This interpretation is supported by observations of an inclined fracture dipping at roughly 12° along the vertical highwall. The depth from the top of the highwall to discrete horizontal fracture traces were tape measured to be 0.7, 1.6, 2.4, 2.96, and 3.6 m. The corresponding depths to reflections, based on the travel time and computed rock mass velocity information, are 0.63, 1.4, 2.49, and 3.72 m, respectively. Although each horizontal fracture could be identified in the radar record, the calculated depth of each fracture might be off by 10 to 20 pct. The radar record also shows a large-amplitude, low-frequency event at about 163 ns, a depth of roughly 4.6 m. This reflection is continuous and nearly horizontal across the record, and it is interpreted as the location of the water table. Specifically, two plausible explanations are offered: First, radar reflection from the phreatic surface (water table). In this case, spreading of the radar wavelet occurs in response to attenuation of energy due to saturated media. Second, wide angle reflection from the adjacent quarry pond surface. Reflections of this type may occur since radar antennas are not focused.

Spectral analysis of the gabbro WARR sounding reveals that the radar energy is broadband, existing between to about 200 MHz (fig. 9). The lower frequency content, compared with the radar surveys conducted at granodiorite sites, suggests that gabbro is more lossy. Specifically, more attenuation occurs with materials characteristic of greater dielectric constants. The most prominent event is roughly 2-1/2 times greater than any other, and it is associated with a relatively low frequency of 10 MHz. This is interpreted to be a reflection from the water table. The remaining packet of frequencies are attributed to reflections from fractures.

Based on the spectral analysis, two processed versions of this radar profile were created. The first processed section, shown in figure 10*B*, represents the results of implementing a low-pass 15-MHz filter. Here, the single, high-amplitude, and continuous reflection event is isolated. The second processed section, shown in figure 10*C*, represents the radar section following the application of a high-pass 150-MHz filter, 40-ns refraction mute, and AGC with a 20-ns window. Again, the resulting radar section is enhanced in amplitude and continuity of reflected events, some not evident on the unprocessed section. Specifically, it is interesting to note that previously unnoticeable reflections now appear below the water table. Moreover, the cusps or undulations in the low-frequency event appears to be attributed to inclined conjugate shear fractures (fig. 10*D*).

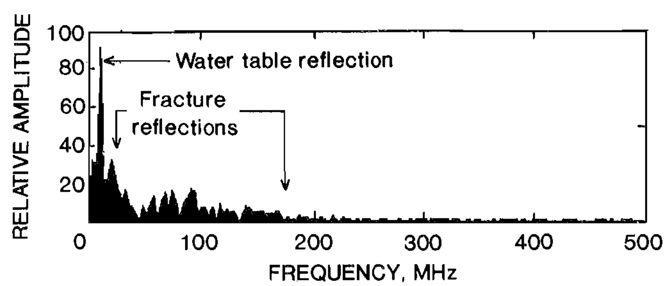

Figure 9.—Spectral analysis of radar profile of Duluth gabbro quarry in northeastern Minnesota.

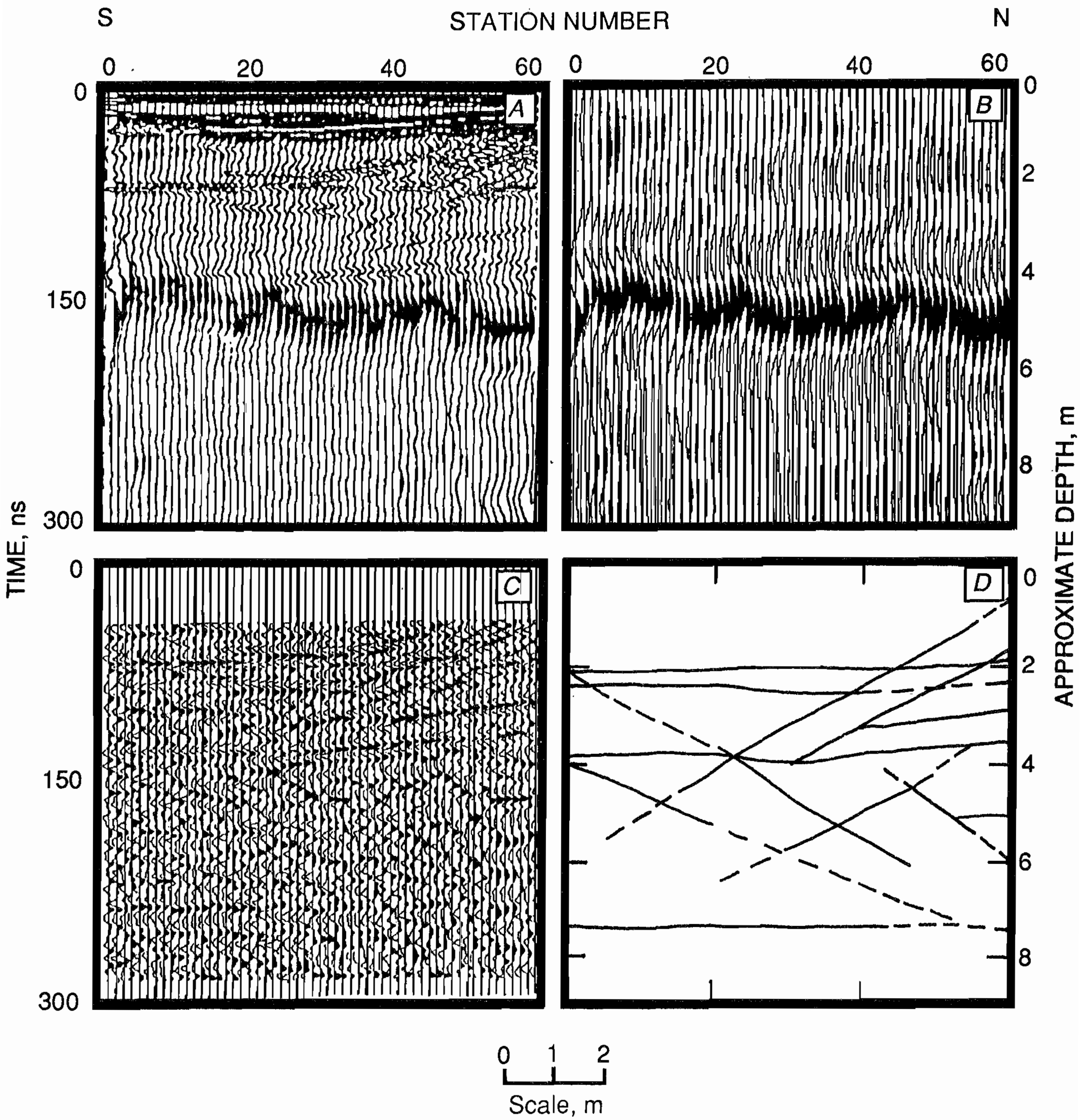

Figure 10.—Analysis of fractures at abandoned Duluth gabbro quarry in northeastern Minnesota. ***A*****, Unprocessed vertical common offset radar profile;** ***B*****, processed (25-MHz low-pass filter) vertical common offset gabbro profile showing the water table reflection;** ***C*****, processed (150-MHz high-pass filter) vertical common offset gabbro profile showing fracture reflections;** ***D*****, mapped highwall fracture distribution.**

CONCLUSIONS

CO radar reflection, using 250-MHz antennas, provides nontechnical personnel with a relatively simple, rapid, and cost-effective means for mapping shallow, small-scale fractures, in igneous rock, at active or abandoned quarries, and outcrops. The actual time required for a survey is governed primarily by site specific acquisition parameters. Upon establishing the appropriate filter settings, record length, and source-to-receiver distance, the survey time is dependent on the number of stacked shots per measurement and total number of measurements; typically, a single measurement requires less than 1 min. It should be noted that the combination of 250-MHz antennas and velocities characteristic of igneous rocks (0.061 m/ns for gabbro and 0.125 m/ns for granodiorite) limit rock mass interrogation to depths greater than about 1.5 m, but less than about 10 m. Depth or distance to fractures can be accurately estimated for this range, and time-shift compensation is necessary only when topographic irregularities exceed 30 cm.

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